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## ON WINDS IN THE LOWER IONOSPHERE AND VARIATIONS OF THE EARTH'S MAGNETIC FIELD

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### ABSTRACT

Increasing indication of interaction between the stratosphere and mesosphere makes it seem probable that effects from the lower atmosphere will not be uncommon among the variations of the earth's magnetic field especially in the form and range of the daily variation of the field. Meteorology may be able to aid space research by identifying effects in the magnetic records that may be of atmospheric origin in order that they not be mistaken for direct solar effects. Extending the work of two earlier articles this paper gives the daily variation of the horizontal intensity of the earth's field for San Juan, Puerto Rico, as the quiet-day average for the 11 years 1948-58 in a form which illustrates seasonal features that the author believes arise from prevailing ionospheric winds. Further, semi-monthly individual 5-day averages of the daily variation are given for San Juan for a period of 12 months in 1957-58 for which a description of the stratospheric circulation at roughly 30 km. altitude (10 mb.) was available.

### 1. INTRODUCTION

Winds in the lower ionosphere probably lead by dynamo action to electric currents there. The magnetic fields of these variable currents, superposed on the earth's main magnetic field which is utilized in the dynamo action, produce small variations in the field. A daily variation<sup>1</sup> has long been known, arising apparently from daily periodic winds in the lower ionosphere produced gravitationally or thermally by the sun. Since there are also prevailing winds in the lower ionosphere it may be that the daily periodic winds can helpfully be thought of as a solar-produced daily distortion of the prevailing winds.

In an article concerning ionospheric current systems caused by non-periodic winds van Sabben [16] has investigated the possible contribution of large-scale prevailing winds to the daily geomagnetic variation. The reader's attention is also called to another article by van Sabben [17], especially to the yearly variation of asymmetry discussed there.

The ionospheric winds, in moving across the lines of force of the earth's main magnetic field, give rise to electromotive forces that may impel electric current flow in the electrically conducting air. It is the vertical component of the main magnetic field that is of principal importance in the dynamo action that leads to the normal daily variation of the field. But the vertical component of the earth's field is considerable only in middle and high latitudes, so that it is mainly the winds of middle and high latitudes that generate the electromotive forces that drive the electric currents.

However, the large-scale current circuit of the daily variation is completed in low latitudes, the pattern of current flow in each hemisphere resembling roughly two large current vortices, one on the day side and a weaker one on the night side. Thus the currents of the daily variation flowing overhead at a low-latitude station are indicative, following the dynamo theory, of the action of winds in middle and high latitudes.

In work which is illustrative of the above, Vestine [18] has studied the behavior of such winds inferred from geomagnetic and ionospheric observations from the low-lati-

<sup>1</sup> The dynamo theory of the quiet-day daily variation of the earth's field is now widely accepted and the present article is written from this point of view.

tude observatory of Huancayo, Peru. In this work concerning the seasonal changes in day-to-day variability of upper-air winds near the 100-km. level of the atmosphere he has remarked that the dynamo electric field responsible for the magnetic diurnal variation is probably the result of a daily distortion of the existing zonal wind patterns.

Chapman [6] has given a very helpful survey of the general subject of regular motions of air in the ionosphere and their geomagnetic relationships. The reader's attention is also called to the recent extensive work of Matsushita and Maeda [13] on the daily variation of the field.

In 1945 the author [22] discussed the possible relation of large-scale air circulation in the ionosphere to variations of the earth's magnetic field and attempted shortly after [23] a comparison of variations of the field, both quiet and disturbed, with atmospheric circulation near the base of the stratosphere as indicated by meteorological maps then available. This work was extended by Wulf and Hodge [24].

## 2. PURPOSE AND BACKGROUND OF THE PRESENT WORK

The main purpose of this article is to stress the part that prevailing winds in the lower ionosphere probably play in the daily variation of the earth's magnetic field, and to emphasize the service that meteorology may be able to render space research by determining what features of the magnetic records may be of atmospheric origin in order that these not be mistaken as arising extraterrestrially, i.e., from direct solar influence. The article extends the work of two earlier ones [20, 21]. It gives the daily variation of the horizontal intensity of the earth's magnetic field at San Juan, Puerto Rico, in a form to illustrate seasonal features of the daily variation that are probably of atmospheric origin. This has been done for two other locations, Honolulu, Hawaii, and Tucson, Ariz., in the two preceding articles [20, 21]. Emphasis is laid on seasonal asymmetry with respect to solar declination.

In view of the part probably played by winds in the daily variation of the field, the meteorology of the lower ionosphere is of importance to geomagnetism. But also it is probable that in geomagnetic observations there is material of help in understanding some of the behavior of the atmosphere lower down. This belief on the part of the author is supported by increasing indications of interaction between the stratosphere and the mesosphere.

Thus, Bossolasco and Elena [4] have given evidence for a relation between radio wave absorption in the *D* region of the ionosphere (largely in the mesosphere) in winter and the temperature of the stratosphere at 10 mb.

Aitken, Kane, and Troim [1] have shown that the electron collision frequency in the *D* region is subject to significant variations that are correlated to pressure variations of the stratosphere. Gregory [9], in measurements of electron densities in the mesosphere (i.e., in the *D* region of the ionosphere) at Christchurch, New Zealand

(43° S.), has given evidence that during winter months increases in radio wave absorption in the mesosphere are correlated with increases in stratospheric temperatures.

With an interaction between the mesosphere and stratosphere clearly indicated, it seems probable to the author that, even though the electric currents of the daily variation of the magnetic field normally flow at a level somewhat above the mesosphere, atmospheric effects from below will be present in the daily variation of the field, and that, on the other hand, solar influences that produce atmospheric changes in the lower ionosphere and mesosphere may in some measure be felt below.

In view of this it appears that the meteorology of the lower atmosphere may be of help to space research. One source of information as to variable solar particle radiation in the vicinity of the earth and incident on the upper atmosphere is the daily continuous magnetic records made at the surface of the earth. Commonly employed in research is the geomagnetic activity index *Kp* (and *Ap* based on it) which is derived from the magnetic records.

If there are effects in the magnetograms, in addition to the normal daily variation, arising from the behavior of the terrestrial atmosphere, it is important that these be identified as such and not taken to be of direct solar origin.

The dynamo theory of the daily variation refers to magnetically quiet days, days which are free from magnetic disturbance. Disturbance effects are ordinarily attributed to solar particle radiation. But there are undoubtedly some deviations from the quiet-day daily variation that arise from atmospheric sources, and these need to be distinguished. The observations suggest that such fluctuations of the field may occur over time intervals from several minutes to several hours. An illustration of what may be one such feature of the longer interval kind is given in some detail in figure 4 of Wulf [21]. In this instance, however, the feature, sometimes spoken of as the Tucson summer midday maximum, occurs during certain months of the year so frequently and in so similar a form that it is generally considered to be a seasonal feature of the daily variation itself.

Dodson, Hedeman, and Stewart [8], in a recent report on solar activity during the first 14 months of the International Years of the Quiet Sun, have made in figures 7 and 8 of that report a comparison of solar behavior and the geomagnetic disturbance index *Kp*. The present author believes that points made in the last paragraph of that report relative to these figures are of much importance and that conditions in the earth's atmosphere constitute another factor influencing geomagnetic disturbance. In this connection the reader is referred to work of Nicholson and Wulf [14].

Hines [10] has called attention to the possibility of wind-induced irregular magnetic fluctuations. That, in some measure, wind-induced magnetic fluctuations occur appears probable from the studies of the winds that

are observed in the dynamo region, such as the work of Kochanski [12] and of Kantor and Cole [11].

A remarkable characteristic of the daily variation of the magnetic field is its frequent large variability from day to day. One source of this is probably the variability from day to day of the prevailing winds in the dynamo region.

Further, there is evidence that certain changes occurring in the lower ionosphere get through to the lower atmosphere and to the surface. Thus, Chrzanowski, Greene, Lemmon, and Young [7] have shown that certain traveling atmospheric pressure waves of infrasonic character observed at the earth's surface at Washington, D.C., are associated with enhanced geomagnetic activity, the waves coming apparently from the auroral-zone ionosphere.

Campbell and Young [5], continuing this type of investigation in Alaska, observed at the earth's surface infrasonic pressure waves originating in auroral disturbances. They also observed an occurrence of what appeared to be a disturbance in the ionosphere produced by a primarily tropospheric pressure wave.

In view of the part probably played by prevailing ionospheric winds in the daily variation of the earth's magnetic field, the above evidence for interaction between the upper and lower atmospheres emphasizes the importance of determining the extent to which the daily magnetic variation may be related to meteorological factors in the atmosphere below. In the next section the monthly average quiet-day daily variation of the horizontal intensity of the field at San Juan, Puerto Rico, for 11 years is given in a form such as to illustrate effects probably due to prevailing winds in the lower ionosphere. (This has been done previously for Honolulu [20] and for Tucson [21]). Following this the daily variation for San Juan is given as individual 5-day averages semi-monthly for a 12-mo. period in 1957-58 for which a description of the circulatory changes that occurred in the high stratosphere was available.

### 3. PRESENTATION OF DATA

In figure 1 are shown, for the five international quiet days of each month, the 12 monthly averages of the daily variation of the horizontal intensity of the earth's field at San Juan for the 11 years 1948-58. These years follow the sunspot maximum of 1947, contain the sunspot minimum of 1954, and extend through the maximum of 1957. They include several years of unusually high sunspot numbers.

For each year, for each month separately, the hourly departures of the horizontal intensity were determined from the row for the mean of the five quiet days in the table of hourly values for the particular month in the corresponding yearbook for the San Juan Magnetic Observatory issued by the U.S. Coast and Geodetic Survey. For each month the 11 values for each hour

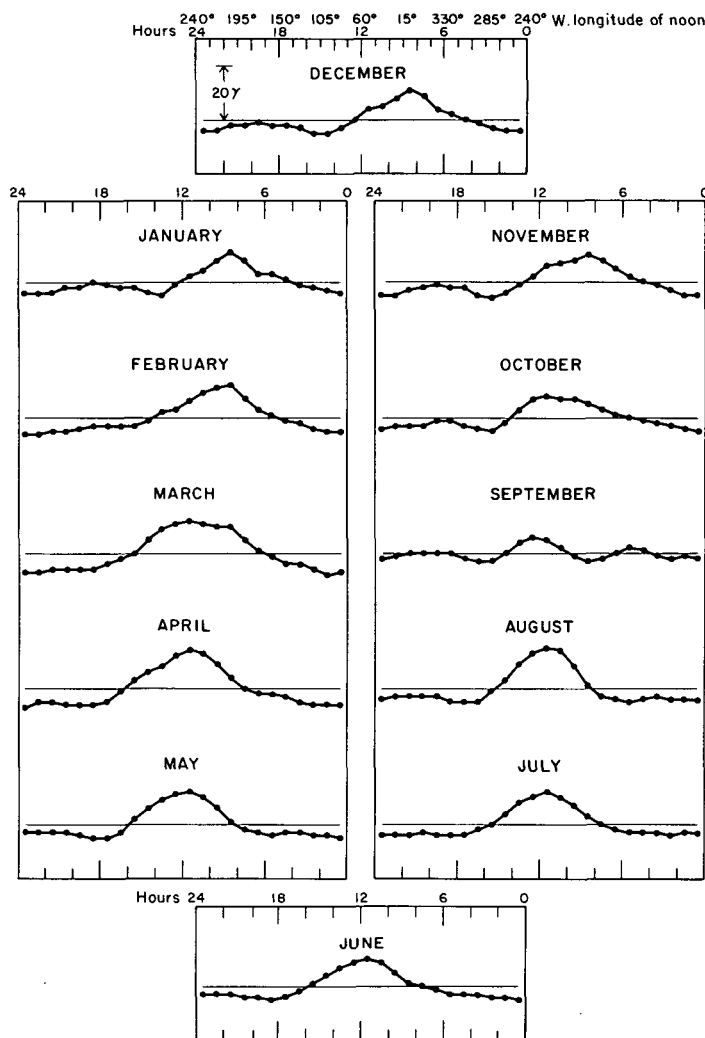


FIGURE 1.—Daily variation of horizontal intensity (in gammas) of the earth's magnetic field at San Juan, Puerto Rico. Monthly averages for the five international quiet days of each month for the 11 years 1948-58. 60th west meridian time.

were averaged, rounding the results to 1 gamma. These were corrected approximately for non-cyclic change and the values plotted in figure 1.

As in the previous two articles [20, 21] the figure is so arranged that the results for months having roughly the same average solar declination are horizontally adjacent to one another. The approximations involved in this were discussed in the article on Honolulu [20]. The arrangement permits one to compare conveniently differences that occur in the form of the daily variation of the field at different times of year but for approximately the same solar declination, that is, for the same geographical latitude of the subsolar point. From the figure it can be seen that at times of essentially the same solar declination on opposite sides of the year the form of the daily variation of the field may differ greatly.

The time scale is made to run from right to left. The desirability of this was explained in the work on Tucson [21]. The author feels that this is of considerable importance in a study such as the present one, and hopes that this procedure may find acceptance by others where geographical characteristics of the large-scale ionospheric winds that produce the daily variation are of interest. The purpose of these figures is mainly to permit one to see for any one observatory the change of the monthly average forms of the daily variation of the field throughout the year at that observatory. The yearly average form of the daily variation may be quite different for different observatories, depending mainly on latitude (see, for example, Vestine, Laporte, Lange, and Scott [19]). No emphasis is placed in the present work on a comparison of the daily variation of the field between different locations.

In the diagrams of the daily variation with the time scale so directed, the map of the appropriate hemisphere (here northern) on Mercator's projection, placed with the longitude of noon corresponding to the time scale, may helpfully be imagined as underprint, as emphasized in the work on Tucson [21]. This permits one to keep in mind geographically, as the geomagnetic variation progresses with the time of day, the approximate longitude of the center of the cap of enhanced ionization and heating in the upper atmosphere [21] that moves throughout the day from east to west approximately under the sun. This heating (for example, in the upper part of the ozone region) may be an important, if not the major, factor in the production of the daily periodic winds. As described above, considerable changes that occur in the quiet-day daily variation of the field, seasonally and especially from day to day, may arise mainly through corresponding changes that occur in the large-scale prevailing winds in the lower ionosphere in which the daily periodic winds are produced.

Referring to figure 1, as at Honolulu [20] and at Tucson [21], a marked difference can be seen between the average forms of the daily variation in March and in September, though solar declination is approximately the same at these times. Similarly, the form for February differs considerably from that for October. The September maximum near noon, not characteristic of February, seems present in October. A suggestion of this can still be seen in November, though the maximum in November is much earlier. In the 9th hour the departure for October is positive, suggesting the rapid seasonal disappearance of the September forenoon minimum, and in November the maximum is already in the 9th hour, which, in figure 1, is characteristic of December, January, and February.

An afternoon minimum in September that persists through December and January has disappeared in February, and this change is continued prominently into March.

The data were also divided into two portions of five and

six years each in order to inquire in how far these monthly averages are representative of the 11 years. The division chosen was the five years prior to and including sunspot minimum 1950-54, and the remaining six years 1948, 1949, 1955-58, as was done for Honolulu and Tucson [20, 21]. The results arranged in the same form as those in figure 1 are shown in figures 2 and 3, respectively. They have been corrected approximately for non-cyclic change.

The results for the two sets of years are in general similar, giving support to the reality of the seasonal characteristics pointed out in figure 1. A majority of the months shows a greater range in the average of the six years (fig. 3) than in the average of the five (fig. 2), in accord with the general tendency for the range of the daily variation to be greater in years of greater sunspot number. The average yearly sunspot number for the six years was 138, while that for the five years was 41.

Some further differences, however, can be seen between the two sets which suggest that there are appreciable differences for any one month between the averages of the five days for that month among the individual contributing 11 years, and this is indeed the case. This may arise in part from the large variability of the daily variation from day to day, even on reasonably quiet days.

In concluding this paper a step will be made in the direction of a day-to-day comparison of the geomagnetic variation with charts of the air circulation in the upper stratosphere (which the author proposes as a research of value) by illustrating the magnetic data in individual 5-day averages semi-monthly over a 12-mo. period for which a description of the changing circulation in the upper stratosphere was available.

Teweles, Rothenburg, and Finger [15] have described the principal changes that occurred in the large-scale stratospheric circulation at the 10-mb. constant pressure surface (near the 31-km. level) over the North American region for the interval July 1957 through June 1958. Prominent among these changes are the giving way of the summer zonal easterlies in high latitudes in the first half of August, the formation of a well marked ridge by early September separating the subtropical easterlies from the polar westerlies, and the change through September with nearly circumpolar westerlies in October.

By the middle of November an extensive anticyclone existed over the Aleutians with a return to roughly circumpolar westerlies by late November. During December there were no great changes in the pattern.

In the latter half of January a series of radical and relatively rapid changes occurred, and by the middle of February a quite different pattern of circulation existed.

Since some of the changes of the magnetic daily variation shown in figure 1 may arise from changes in large-scale winds in the lower ionosphere, it seems natural to inquire whether they may show some relation to the changes of the large-scale winds in the upper stratosphere.

Figure 1, however, illustrates an average monthly behavior over a number of years. A closer comparison in

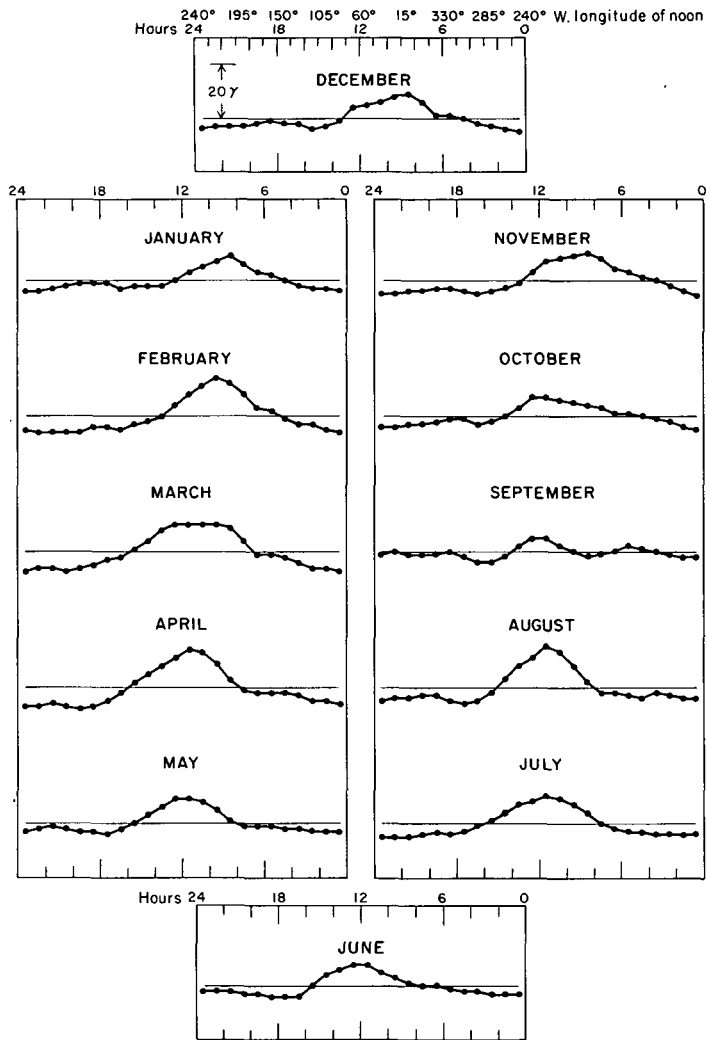


FIGURE 2.—Daily variation of horizontal intensity (in gammas) of the earth's magnetic field at San Juan, Puerto Rico. Monthly averages for the five international quiet days of each month for the five years 1950–54. 60th west meridian time.

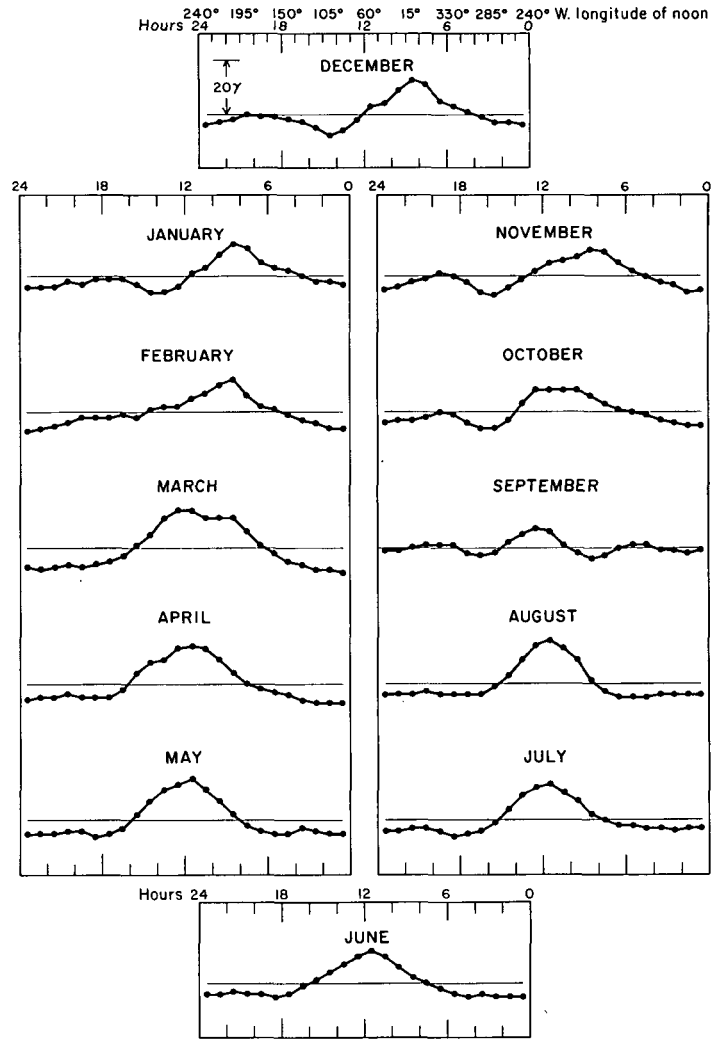


FIGURE 3.—Daily variation of horizontal intensity (in gammas) of the earth's magnetic field at San Juan, Puerto Rico. Monthly averages for the five international quiet days of each month for the six years 1948, 1949, 1955–58. 60th west meridian time.

time could be made by studying the changes that are present in the daily variation for these individual months of 1957–58. These months contributed, of course, to the averages of figure 1, that is, they contributed the averages of their five international quiet days. The five days might, in general, come at any time during the month, as, for example, all five near the end of the month. A somewhat closer comparison will be made in what follows, partly as a step toward the use of the data on a daily basis, as has been suggested in an earlier paper by the author [20]. The complications that geomagnetic disturbances would occasion in such a study were discussed there.

Ordinarily there will be in any one month a number of reasonably quiet days with which the changing form and range of the daily variation, relative to the average

changes shown in figure 1, may be fairly satisfactorily followed. Figure 4 is an attempt to illustrate this. The description given by Teweles, Rothenburg, and Finger [15] of the changes in the air circulation in the upper stratosphere is on a time scale appreciably finer than monthly. Thus it was in the first half of August that the summer easterlies began to give way in high latitudes.

In figure 4 there is given the average daily variation of the horizontal intensity of the field (corrected approximately for non-cyclic change) at San Juan for five relatively quiet days in the first half and separately in the second half of each individual month for the 12-mo. interval discussed by Teweles, Rothenburg, and Finger [15]. It should be mentioned that this was not an especially quiet period geomagnetically, it being at the maximum of the last sunspot cycle during the International Geophysical Year.

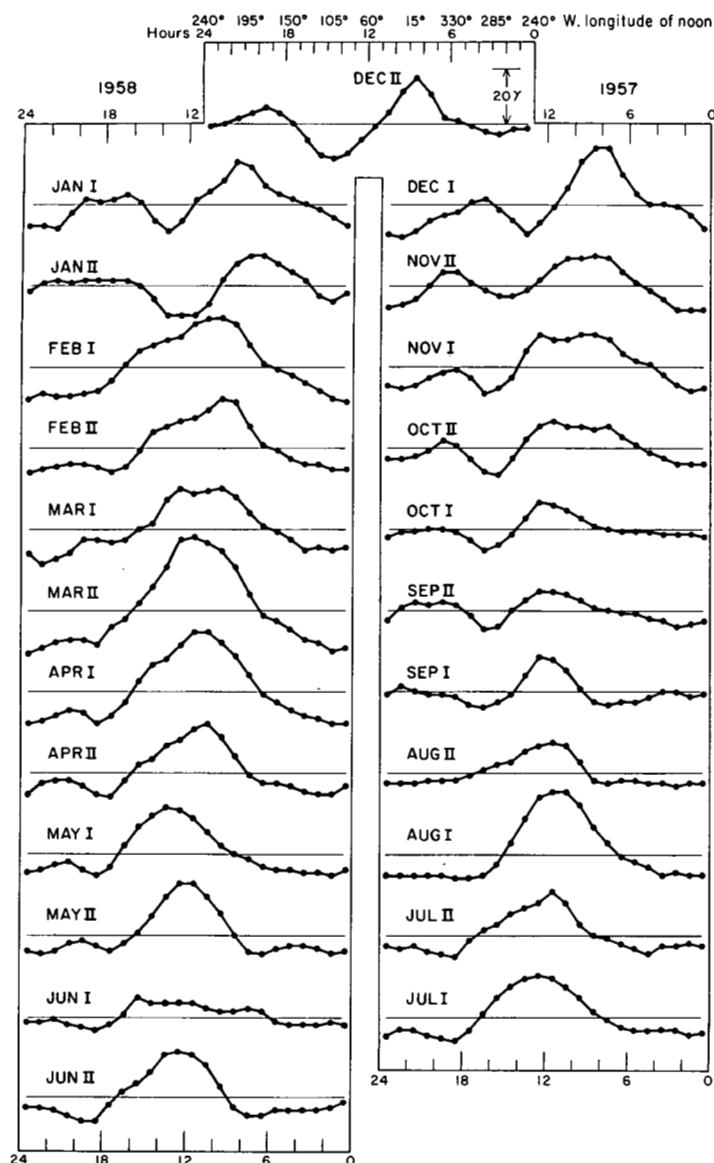


FIGURE 4.—Daily variation of horizontal intensity (in gammas) of the earth's magnetic field at San Juan, Puerto Rico. Individual five-day averages for five relatively quiet days in each half of each of the 12 months July 1957 through June 1958. The second half of December 1957 is placed at the top since it contains the solstice. 60th west meridian time.

To select the five relatively quiet days in each half-monthly period an arbitrary rule based on the daily sum of  $ak$  was used.<sup>2</sup> It should be emphasized, however, that intelligent selection of days could be made on the basis of

<sup>2</sup> The five days in each half of each month (the first 15 days and the remainder) were chosen as the days having the smallest sum of the eight local  $ak$  values computed from the corresponding values of San Juan's 3-hr.-range index  $k$  contained in *Bulletins 12 l* and *12 m 1* of the International Association of Geomagnetism and Aeronomy [2, 3], following the directions for  $ak$  given in the Introduction of these *Bulletins*. The sum was taken for the 24-hr. interval from 3 hr. U.T. of the day in question to 3 hr. U.T. of the next day, this interval approximating the 60° W. meridian time day. Where, in choosing the last of the five days, two days had the same  $ak$  sum, the one having the smaller  $ak$  value for the next 3-hr. interval, 3-6 hr. U.T. of the next day, was chosen, this interval containing the last hour of the 60° W. meridian time day.

more than one consideration. As an example, a day with some disturbance in the first few or last few hours of the local day might have the major portion of the daily variation showing clearly in the record, i.e., in the magnetogram.

In general, a careful appraisal of all disturbance in the magnetic record on each day should be made in such a study from day to day as that proposed in the present papers [20, 21]. It would be important to avoid missing disturbance in the magnetograms that might have arisen from an atmospheric source.

Although each curve of figure 4 is an average of but five individual days, the figure shows a rather regular change<sup>3</sup> which seems to be mainly the quiet-day seasonal change shown in the 11-yr.-average curves of figure 1. However, the five daily curves, of which each of the curves of figure 4 is the average, may differ greatly from one another. A tendency nevertheless toward retaining certain seasonally characteristic features seems to be present. The author plans to continue with a study of the variability from day to day of the daily variation of the field.

Figure 4 suggests that the seasonal change, which figure 1 indicates takes place on the average from January to March, occurred in 1958 mainly from January to February, and more closely from the latter part of January to the first part of February. This stands in a certain correspondence with the change observed at about this time in the upper stratosphere [15]. However, no implication is intended that figure 4 demonstrates a relation between the changes which it portrays and the changes in the stratospheric circulation over this period. But figure 4 does give support, in the author's opinion, to his belief that it is practicable to make potentially valuable comparison of the day-to-day changes in the daily variation of the earth's magnetic field with the day-to-day changes in the large-scale winds in the upper stratosphere, and thereby to discover whether such a relation does exist.

#### 4. CONCLUSIONS

From the character of the seasonal change of the daily variation of the earth's magnetic field at Honolulu, Tucson, and San Juan discussed in the course of the present work and from evidence drawn from work of others concerning interaction between the mesosphere and stratosphere, it is concluded that changes in the prevailing winds in the lower ionosphere probably produce recognizable changes in the daily variation of the earth's field, and that the changes in these winds probably bear some relation to changes in the winds of the upper stratosphere. The author believes that a current day-to-day comparison of the daily magnetic variation with daily charts of the large-scale patterns of the air circulation in

<sup>3</sup> The curve for Jun I is an exception. The fifth day chosen by the rule used here contained evident disturbance, which accounts for the maximum in the 16th hour but not for the overall small range. Only one of the five days in this instance had a large range of daily variation of relatively normal form.

the high stratosphere constitutes a valuable research, and that meteorology may be able to aid space research by identifying as of atmospheric origin some disturbance in the magnetic records that otherwise might be mistaken as arising from direct solar influence.

# REFERENCES

1. A. C. Aikin, J. A. Kane, and J. Troim, "Some Results of Rocket Experiments in the Quiet D Region," *Journal of Geophysical Research*, vol. 69, No. 21, Nov. 1, 1964, pp. 4621-4628.
2. J. Bartels, A. Romaña, and J. Veldkamp, "Geomagnetic Data 1957. Indices K and C, Rapid Variations," International Association of Geomagnetism and Aeronomy, *Bulletin* No. 12 l, 1961.
3. J. Bartels, A. Romaña, and J. Veldkamp, "Geomagnetic Data 1958. Indices K and C," International Association of Geomagnetism and Aeronomy, *Bulletin* No. 12 m 1, 1962.
4. M. Bossolasco and A. Elena, "Absorption de la Couche D et Température de la Mesosphere," *Comptes Rendus de l'Académie des Sciences (Paris)*, vol. 256, May 20, 1963, pp. 4491-4493.
5. W. H. Campbell and J. M. Young, "Auroral-Zone Observations of Infrasonic Pressure Waves Related to Ionospheric Disturbances and Geomagnetic Activity," *Journal of Geophysical Research*, vol. 68, No. 21, Nov. 1, 1963, pp. 5909-5916.
6. S. Chapman, "Regular Motions in the Ionosphere: Electric and Magnetic Relationships," *Bulletin of the American Meteorological Society*, vol. 42, No. 2, Feb. 1961, pp. 85-100.
7. P. Chrzanowski, G. Greene, K. T. Lemmon, and J. M. Young, "Traveling Pressure Waves Associated with Geomagnetic Activity," *Journal of Geophysical Research*, vol. 66, No. 11, Nov. 1961, pp. 3727-3733.
8. H. W. Dodson, E. R. Hedeman, and F. L. Stewart, "Solar Activity during the First 14 Months of the International Years of the Quiet Sun," *Science*, vol. 148, No. 3675, June 4, 1965, pp. 1328-1331.
9. J. B. Gregory, "The Influence of Atmospheric Circulation on Mesospheric Electron Densities in Winter," *Journal of the Atmospheric Sciences*, vol. 22, No. 1, Jan. 1965, pp. 18-23.
10. C. O. Hines, "Wind-Induced Magnetic Fluctuations," *Journal of Geophysical Research*, vol. 70, No. 7, Apr. 1, 1965, pp. 1758-1761.
11. A. J. Kantor and A. E. Cole, "Zonal and Meridional Winds to 120 Kilometers," *Journal of Geophysical Research*, vol. 69, No. 24, Dec. 15, 1964, pp. 5131-5140.
12. A. Kochanski, "Atmospheric Motions from Sodium Cloud Drifts," *Journal of Geophysical Research*, vol. 69, No. 17, Sept. 1, 1964, pp. 3651-3662.
13. S. Matsushita and H. Maeda, "On the Geomagnetic Solar Quiet Daily Variation Field during the IGY," *Journal of Geophysical Research*, vol. 70, No. 11, June 1, 1965, pp. 2535-2558.
14. S. B. Nicholson and O. R. Wulf, "The Role of Quiet Days in the Mechanism of Geomagnetic Activity," *Publications of the Astronomical Society of the Pacific*, vol. 64, No. 380, Oct. 1952, pp. 265-270.
15. S. Teweles, L. Rothenberg, and F. G. Finger, "The Circulation at the 10-Millibar Constant Pressure Surface over North America and Adjacent Ocean Areas, July 1957 through June 1958," *Monthly Weather Review*, vol. 88, No. 4, Apr. 1960, pp. 137-150.
16. D. van Sabben, "Ionospheric Current Systems Caused by Non-Periodic Winds," *Journal of Atmospheric and Terrestrial Physics*, vol. 24, Nov. 1962, pp. 959-974.
17. D. van Sabben, "North-South Asymmetry of  $S_q$ ," *Journal of Atmospheric and Terrestrial Physics*, vol. 26, Dec. 1964, pp. 1187-1195.
18. E. H. Vestine, "Seasonal Changes in Day-to-Day Variability of Upper Air Winds Near the 100-km. Level of the Atmosphere," *Transactions of the American Geophysical Union*, vol. 39, No. 2, Apr. 1958, pp. 213-223.
19. E. H. Vestine, L. Laporte, I. Lange, and W. E. Scott, "The Geomagnetic Field, Its Description and Analysis," Chap. VII in *Publication 580*, Carnegie Institution of Washington, 1947.
20. O. R. Wulf, "A Possible Effect of Atmospheric Circulation in the Daily Variation of the Earth's Magnetic Field," *Monthly Weather Review*, vol. 91, Nos. 10-12, Oct.-Dec. 1963, pp. 520-526.
21. O. R. Wulf, "A Possible Effect of Atmospheric Circulation in the Daily Variation of the Earth's Magnetic Field. II," *Monthly Weather Review*, vol. 93, No. 3, Mar. 1965, pp. 127-132.
22. O. R. Wulf, "On the Relation between Geomagnetism and the Circulatory Motions of the Air in the Atmosphere," *Terrestrial Magnetism and Atmospheric Electricity*, vol. 50, No. 3, Sept. 1945, pp. 185-197.
23. O. R. Wulf, "A Preliminary Study of the Relation between Geomagnetism and the Circulatory Motions of the Air in the Atmosphere," *Terrestrial Magnetism and Atmospheric Electricity*, vol. 50, No. 4, Dec. 1945, pp. 259-278.
24. O. R. Wulf and M. W. Hodge, "On the Relation between Variations of the Earth's Magnetic Field and Variations of the Large-Scale Atmospheric Circulation," *Journal of Geophysical Research*, vol. 55, No. 1, Mar. 1950, pp. 1-20. (See especially figure 8.)

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